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SUMMARY

Frequency-response data, in terms of boiler-inlet impedance, were obtained for a forced-flow single-tube boiler with inserts. The flow rate of the test fluid was sinusoidally varied about a mean value. Magnitudes and phase angles of the pressure and flow perturbations were measured at the boiler inlet. The test section was a shell and tube heat exchanger with a plug and spring in the subcooled liquid region and a spirally wound spring in the two-phase region. Freon-113 was the test fluid. The inner tube had an inside diameter of 0.430 inch (1.09 cm) and a heated length of 32 inches (81.3 cm). Hot water flowed countercurrent to the Freon flow in the annulus between the inner and outer tubes. The boiler-inlet impedance had a negative real part over some frequency range for exit vapor qualities greater than about 40 percent. The boiler became unstable when the feedline resistance was reduced and made equal to the magnitude of the boiler impedance at -180° phase angle.

INTRODUCTION

The occurrence of unsteady flow of the working fluid in a Rankine energy-conversion system can be detrimental to system performance. Unsteady flow in the system can originate as a result of incompatibility, in terms of dynamic characteristics, between the components of the system. One of the most important components in a Rankine system is the boiler. Therefore, a program was initiated at the Lewis Research Center to obtain experimental data on their dynamic characteristics. Dynamic characteristics of a single-hollow-tube boiler, in terms of inlet impedance, were reported in reference 1. The results of the work in reference 1 showed that the boiler-inlet impedance had a negative real part over some frequency range, implying the existence of a region where the boiler may be a source of instability if improperly matched to the system. In addition, the magnitude of the boiler-inlet impedance increased with increasing boiler exit qualities below perturbation frequencies of approximately 0.6 cps (0.6 Hz). Above 0.6 cps (0.6 Hz) the relation between the magnitude of the impedance and the boiler exit quality was not well defined. The maximum boiler exit quality obtained in the work of reference 1 was of the order of 60 percent. The limitation on the boiler exit quality was caused by the transition to film boiling in the test section.

The objective of the work reported herein was to obtain additional data on the dynamic characteristics of single-tube boilers over a larger boiler exit quality range. To improve the heat transfer to the working fluid, inserts were placed in the flow passage of the boiler. A spirally wound spring was brazed along the entire length of the inner surface of the boiler tube to induce liquid flow on the wall. In addition, a rod was inserted at the boiler entrance so that the subcooled liquid flowed through a spiraled annular passage for a short distance (8 in. (20.3 cm)). The boiling fluid was Freon-113 (trichlorotrifluoroethane). The test section was a shell and tube heat exchanger with hot water flowing countercurrent in the annulus between the two tubes. The inner tube was stainless steel with an inner diameter of 0.430 inch (1.09 cm) and a heated length of 32 inches (81.3 cm). Vapor state at the boiler outlet ranged from a quality of 20 percent to a superheat of 10° F (5.6° K). The boiling fluid flow rate (and pressure) was sinusoidally varied about a mean value, and measurements were made of the pressure and flow variations at the boiler entrance.

DEFINITION AND MEASUREMENT OF BOILER-INLET IMPEDANCE

The use of frequency-response methods is based on the hypothesis that, for small amplitude disturbances, the boiler can be treated as a linear element. For a linear boiler with constant pressure at the outlet, the complex ratio (amplitude ratio and phase difference) of boiler-inlet pressure perturbation to inlet flow perturbation for sinusoidal perturbations is a function of frequency and boiler parameters only. This complex ratio of pressure perturbation to flow perturbation is analogous to the input impedance of a four-terminal electrical network with the output shorted. Thus, the complex ratio of pressure perturbation at the boiler inlet to flow perturbation at the boiler inlet with constant pressure at the outlet is referred to as the boiler-inlet impedance.

The boiler-inlet impedance was obtained experimentally by oscillating the open area of a valve in the feed system about a mean area and measuring the pressure and flow at the boiler inlet. The pressure and flow signals were analyzed by a frequency-response analyzer. This analyzer computed the magnitude and phase (relative to a sinusoidal reference oscillator) of the sinusoidal content of the pressure and flow signals at the frequency of the reference oscillator. Since the analyzer required that the pressure and flow signals have a sinusoidal content at exactly the frequency of the reference oscillator, the reference oscillator was used to drive the valve in the feed system.

APPARATUS AND PROCEDURE

Description of Facility

The facility used to obtain the frequency response data, shown in the schematic drawing of figure 1, was a two-loop system. Water in the heating fluid loop was heated by steam in a multitube heat exchanger and pump fed through the annulus of the boiler. The Freon loop included a gear pump that provided flow to the boiler. Downstream of the gear pump was an accumulator which prevented flow perturbations out of the pump from traveling to the boiler. The accumulator, by acting as a quasi-constant pressure supply, permitted controlled flow and pressure oscillations to be put into the boiler by an electrohydraulically controlled globe valve located between the accumulator and boiler. The valve stem was oscillated sinusoidally about a mean position to impose oscillations on the mean flow. The Freon flow through the boiler was vertically upward.

The boiler (fig. 2) was a single-tube shell and tube heat exchanger. The inner tube was stainless steel with an inner diameter of 0.430 in. (1.09 cm) and a wall thickness of 0.035 inch (0.089 cm). The outer tube had an inner diameter of 0.680 inch (1.73 cm). Total heated length of the boiler was 32 inches (81.3 cm). A spirally wound spring ($1\frac{1}{4}$ in. (3.17 cm) pitch) was brazed to the inner surface of the inner tube. The spring extended from approximately 3 inches (7.62 cm) upstream of the heated section to 3 inches (7.62 cm) downstream of the heated section. The spring was made from 1/16-inch- (0.16-cm) diameter stainless-steel stock. At the boiler entrance a brass rod 0.305 inch (7.75 mm) in diameter by 8 inches (20.3 cm) long was inserted into the flow passage (fig. 2). The rod made contact with the spring so that the entering liquid flowed through a spiraled annular passage. The rod extended 5 inches (12.7 cm) into the heat-transfer region of the boiler.

A plenum tank was located downstream of the boiler. The end of the boiler tube extended into the plenum tank for a distance of about 3 inches (7.62 cm) to prevent liquid buildup at the boiler outlet. A 0.870-inch (22.1-mm) inside-diameter tube connected the plenum tank to the condenser. The condenser consisted of a large volume tank (70 gal ($0.26\ m^3$)), open to the atmosphere, with water flowing in coiled tubing inside the tank. The flow passage from the plenum tank to the condenser was large enough so that no measurable pressure drop existed between these two points.

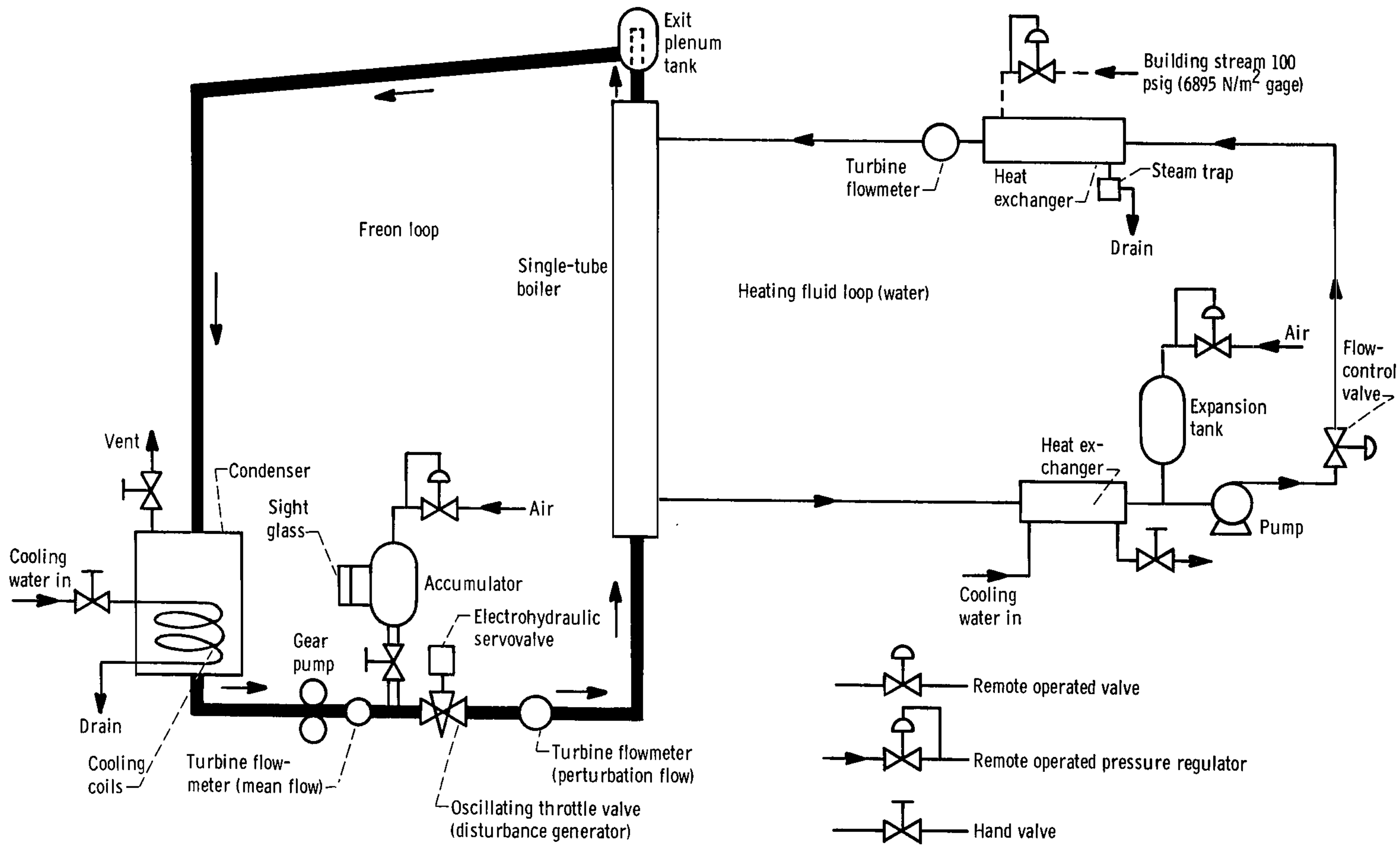
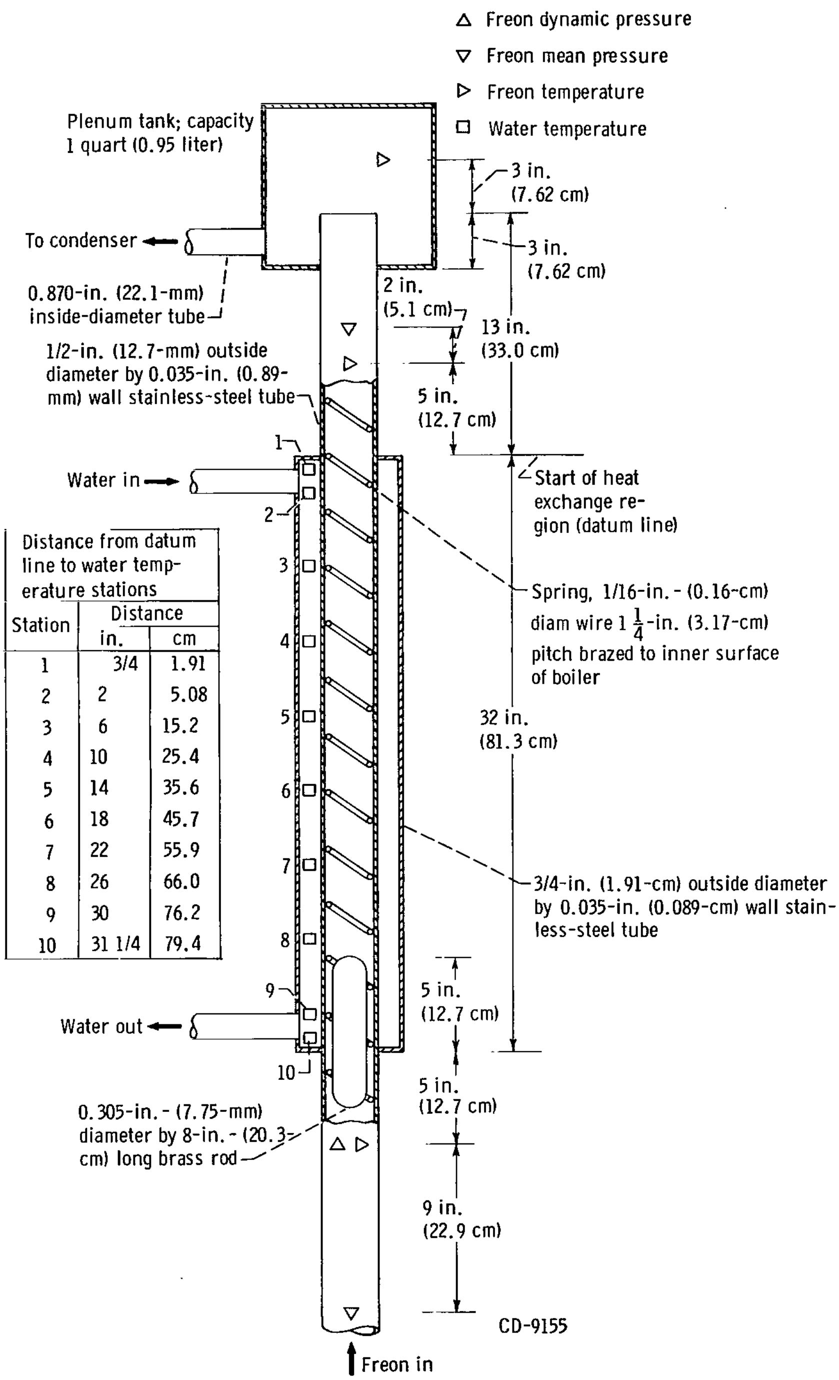


Figure 1. - Boiling dynamics facility.



Distance from datum line to water temperature stations

Station	Distance, in.	Distance, cm
1	3/4	1.91
2	2	5.08
3	6	15.2
4	10	25.4
5	14	35.6
6	18	45.7
7	22	55.9
8	26	66.0
9	30	76.2
10	31 1/4	79.4

Figure 2. - Schematic drawing of single-tube-boiler test section with spring and plug.

Instrumentation

Instrumentation was provided to measure steady-state values of Freon flow rate, water flow rate, Freon pressures and temperatures at the inlet and outlet of the boiler, and the water temperature in the boiler. Dynamic instrumentation was provided to measure Freon pressure and liquid Freon flow rate at the boiler inlet.

Steady state. - Freon and water flow rates were measured with commercial turbine flowmeters. The Freon flowmeter was located between the pump and the accumulator. The water flowmeter was located between the boiler and the heat exchanger used to heat the water. The locations of the Freon pressure and temperature measuring stations are shown in figure 2. Freon pressures were measured at the boiler inlet and outlet with Bourdon tube pressure gages. Copper-constantan thermocouples (bare junction, 0.005-in. (0.127-mm) wires) were used to measure temperatures. Freon temperature was measured at the boiler inlet, outlet, and in the plenum tank with the thermocouple immersed in the fluid stream at right angles to the flow direction. Water temperature in the boiler was measured at the positions shown in figure 2.

Dynamic. - A commercial frequency-response analyzer was used to compute the magnitude and phase relative to the reference oscillator of the measured Freon pressure and flow perturbations at the boiler inlet.

Freon pressure perturbations were measured with a flush-mounted quartz pressure transducer located 5 inches (12.7 cm) upstream of the heated section of the boiler (fig. 2). The pressure signal was conditioned by a tracking band-pass filter which was included with the frequency-response analyzer. Whenever the perturbation frequency was selected, the band-pass filter automatically centered itself about this frequency.

Freon flow perturbations were measured with a turbine flowmeter located between the accumulator and boiler inlet (fig. 1). The flowmeter pulses were amplified and limited to a fixed amplitude. Therefore, the time-average of these pulses was proportional to pulse rate. Since pulse rate was proportional to flow rate, the average was proportional to flow rate. Therefore, the perturbations in the average were proportional to perturbations in flow. The flow signal was conditioned by the band-pass filter. Thus, the high-frequency components and the steady-state level of the flowmeter signal were rejected, and the perturbations at the selected frequency were passed without amplitude or phase error.

Procedure

Calibration. - The quartz crystal pressure transducer was calibrated by applying known pressures and recording the voltage output. Calibration curves for the turbine flowmeters were supplied by their manufacturers. It was assumed that the transducer and the turbine flowmeter followed their steady-state calibration curves over the range of their frequency-response limits. The nominal resonant frequency of the pressure transducer was quoted by the manufacturer to be 60 000 cps (60 000 Hz). The frequency-response limit of the turbine flowmeter was determined experimentally to be about 4 cps (4 Hz). The experimental procedure was to flow all liquid through a hollow tube, perturb the flow, and measure the response of pressure to flow. The results were then compared with the theoretical response. The theoretical response of pressure to mass flow for a short (relative to acoustic wavelength) all-liquid line, should be of the form $R + j\omega(l/A)$, where R is the slope of steady-state pressure drop against mass flow curve, ω is the angular frequency of oscillation, l is the length of the line, and A is the cross-sectional area of the line. The frequency at which the phase angle of the measured response deviated from this form by more than 5° was taken as the upper frequency-response limit of the turbine flowmeter.

The frequency-response analyzer was checked by applying sinusoidal voltages to a simple electrical circuit. A voltage in the circuit was analyzed by the frequency-response analyzer. The measured response was compared with the calculated response, and the agreement was satisfactory from 0.01 to 90 cps (0.01 to 90 Hz).

Frequency-response tests. - It was desired to obtain the dynamic data over as wide a range of heat fluxes and exit vapor qualities as possible. The water flow rate was held at approximately the same value for all the runs. The inlet water temperature was adjusted to three different levels and held constant over a range of Freon mean flow rates. At a given water inlet temperature, the Freon mean flow rate was varied in order to obtain different exit qualities. The inlet temperature of the Freon was held constant during each frequency-response run.

For a particular run, the general operating procedure consisted in setting mean Freon flow rate, water flow rate, and water inlet temperature. After conditions had stabilized, the accumulator in the Freon loop (fig. 1) was charged with air and opened to the system. When the liquid level in the accumulator had stabilized, the mean pressures at the boiler inlet and outlet were recorded from the Bourdon tube pressure gages. Then the pressure gages were valved off from the system, and the oscillating throttle valve (fig. 1) was actuated. The throttle valve was operated over a frequency range from 0.04 to 4.0 cps (0.04 to 4.0 Hz). The amplitude of the throttle area variation was kept small, relative to the mean open area, to minimize nonlinear effects.

At each frequency, the magnitude and phase angle (relative to the command signal) of the inlet pressure and Freon flow perturbations were read from the frequency-response analyzer. Boiler-inlet impedance (magnitude and phase) was plotted as a function of frequency at the time the tests were made. In so doing, a thorough investigation could be made of frequency ranges where the results showed rapid changes. The Freon mean flow rate, water flow rate, and water inlet temperature, were continuously monitored to ensure that the mean operating conditions remained constant. All mean flow rates and temperatures were recorded approximately every half hour.

Natural oscillation tests. - For the runs that gave negative values of boiler-inlet impedance, additional tests were performed to determine if the boiler could be made to go into natural oscillations. This was done by reducing the feedline impedance (by further opening the throttle valve) while maintaining the steady-state conditions. The accumulator was left open to the system, and the oscillator that drove the electrohydraulically operated throttle valve was turned off. The throttle valve was opened slightly, and the Freon pump speed was adjusted in order to maintain the desired steady-state Freon flow. This procedure of valve opening and flow adjustment was continued until either the boiler became unstable or the valve opening reached its maximum value. Throughout this procedure the valve was not oscillating. Boiler instability was characterized by large amplitude pressure and flow oscillations.

Pressure drop. - For the steady-state pressure-drop measurements the oscillating throttle valve was not actuated and the accumulator was not open to the system. The steady-state pressures were recorded at the boiler inlet and outlet from the Bourdon tube pressure gages.

RESULTS

Tabulation of Data

The results of dynamic tests are presented in tables I and II. Table I gives the mean operating conditions for each run for which dynamic measurements were made. The runs are arranged in order of increasing exit vapor quality for a given water inlet temperature (station 1). Exit quality was calculated from a heat balance by assuming that saturation conditions corresponding to the pressure P_o existed at the boiler outlet. (All symbols are defined in the appendix.)

The tabulated values of Freon inlet pressure include the hydrostatic head. The subcooled length, from the beginning of the heated section, was calculated from heat balances, with the assumption that there was no pressure drop from the boiler inlet to the location where the liquid Freon reached the saturation temperature corresponding to the inlet pressure. The two values of Freon outlet temperature, as measured at two locations (t_{Fo} and t_{Fp}), do not agree with the saturation temperature at the outlet. The disagreement is attributed to nonequilibrium and/or phase stratification in the flow passage. The location of the water temperature stations are shown in figure 2.

The boiler perturbation data are given in table II. The magnitude and phase angle relative to the oscillator are given for the Freon flow and boiler inlet pressure. Boiler-inlet impedance is tabulated in terms of magnitude and phase. The phase angle of the boiler impedance is the difference between the phase of the pressure perturbation relative to the oscillator and the flow perturbation relative to the oscillator.

Steady-State Pressure Drop

The results of steady-state pressure-drop tests performed independently of the dynamic tests are shown in figure 3. Pressure drop is plotted as a function of Freon flow rate for three different water inlet temperatures. The independent pressure-drop tests are indicated by open symbols in the figure, and solid symbols represent data from table I. Vapor exit qualities (or superheat, tailed symbols) are denoted by the numbers next to the symbols. The pressure drop that is presented in figure 3 is the Freon absolute inlet pressure minus the pressure in the condenser (atmospheric). This value represents the

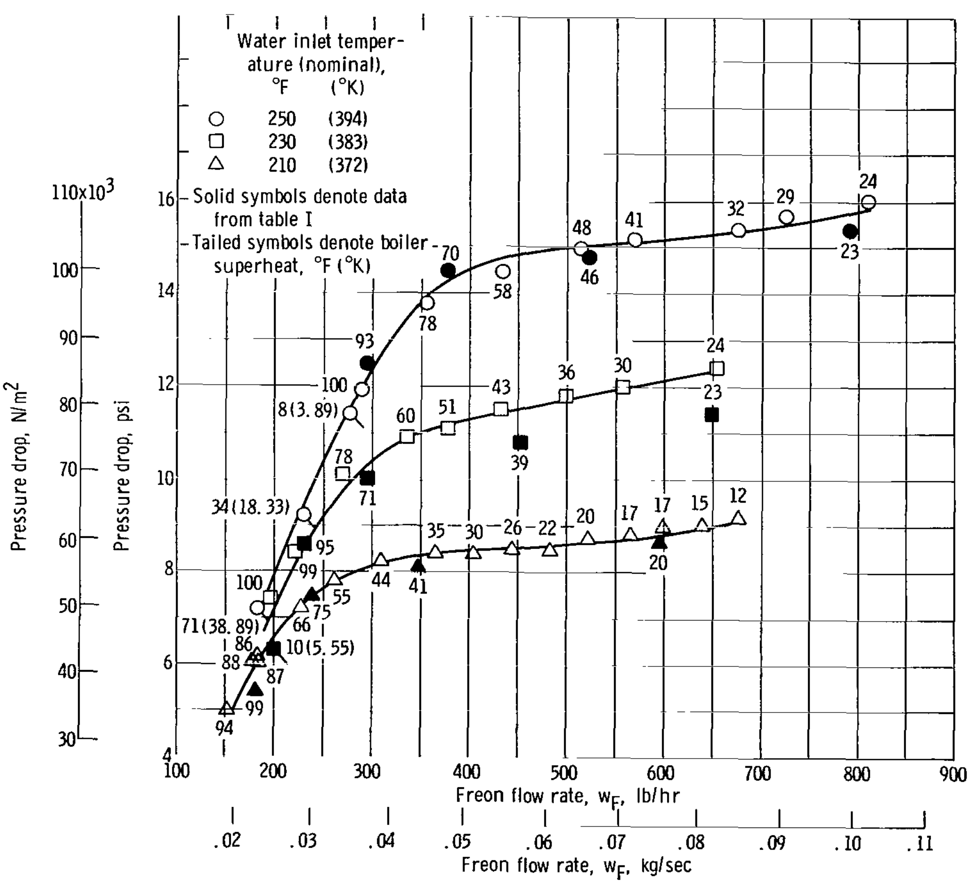


Figure 3. - Pressure drop from boiler inlet to condenser as function of flow rate for different values of water inlet temperature and Freon exit quality.

pressure drop from the boiler inlet to the plenum tank since the measured pressure drop from the plenum to the condenser was negligible for the range of conditions of this test.

Investigations of boiling pressure drop (ref. 2) have shown regions where the curve of pressure drop as a function of flow has a negative slope. The data presented in figure 3 show no evidence of having a negative slope region over the range of conditions investigated.

Frequency-Response Results

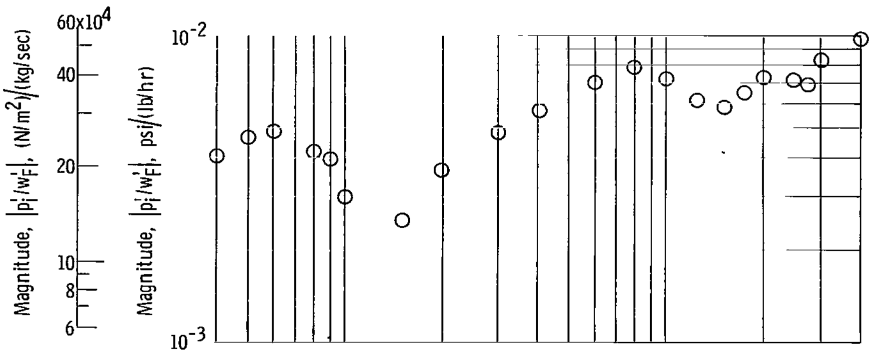
Boiler-inlet impedance as a function of perturbation frequency is shown in figures 4 to 8 for data obtained with a nominal water inlet temperature of 230° F (383° K). The data (runs 5 to 9 of table II) are arranged in order of increasing exit quality. The results obtained from this series of runs are representative of all the runs.

Typical results for the lowest exit quality runs (about 20 percent) are shown in figure 4. The magnitude of the boiler-inlet impedance (fig. 4(a)) shows a general trend to increase with frequency with several dips and peaks over the frequency range investigated. The phase angle (fig. 4(b)) starts at 0° and increases to 50° at 4.0 cps (4.0 Hz). The phase angle curve also has several dips and peaks over the frequency range. A polar plot of the data for this run is shown in figure 4(c). Faired values of magnitude and phase taken from figures 4(a) and (b) were used to construct the polar plot. The dips and peaks in magnitude and phase show up as loops and waviness in the polar plot.

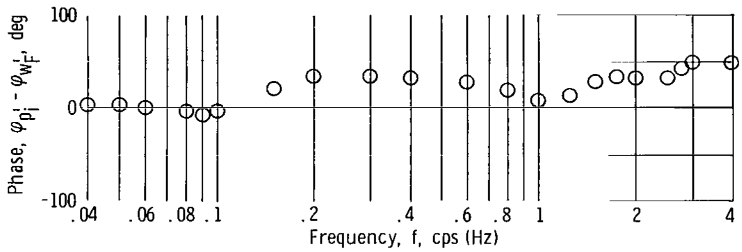
The results of an intermediate exit quality run (about 40 percent) are shown in figure 5. The magnitude (fig. 5(a)) is characterized by sharp dips and only a slight tendency to increase with frequency. The phase (fig. 5(b)) starts at zero and increases with frequency with larger dips and peaks than those obtained with the 20-percent quality run. The polar plot (fig. 5(c)) is characterized by several loops.

The data for the higher quality and superheated outlet vapor runs are presented in figures 6 to 8. The magnitudes of these runs are approximately constant up to 0.10 cps (0.10 Hz). Beyond this frequency, the magnitude decreases with a slope of -1 over a portion of the frequency range. This characterizes a first-order dropoff. At the higher frequencies, sharp dips and peaks are present. The phase shift for these runs shows a continuous increase in phase lag up to about 2 cps (2 Hz). This continuous increase in phase lag suggests that a dead-time phenomenon is a contributing factor to the results.

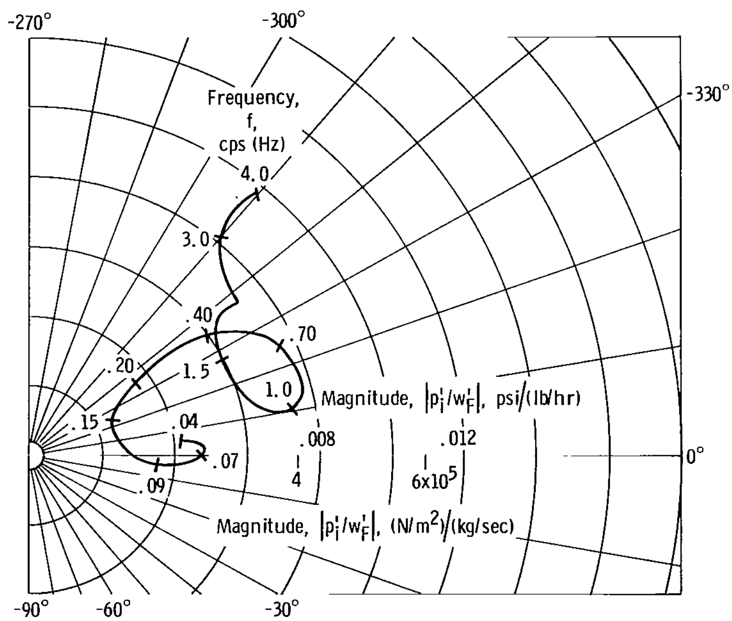
Thus, the boiler-inlet impedance approaches a dead time with a first-order dropoff in magnitude as the exit vapor quality increases. The low-frequency magnitude increases with increase in exit vapor quality caused by the increase in the slope of the pressure-drop - flow curve with increase in quality (fig. 3). The polar plots of the boiler-inlet impedance in figures 6(c), 7(c), and 8(c) show the real part of the impedance to be negative (phase angles between -90° and -270°) over some frequency range for each of the runs.



(a) Magnitude of boiler-inlet impedance as function of frequency.

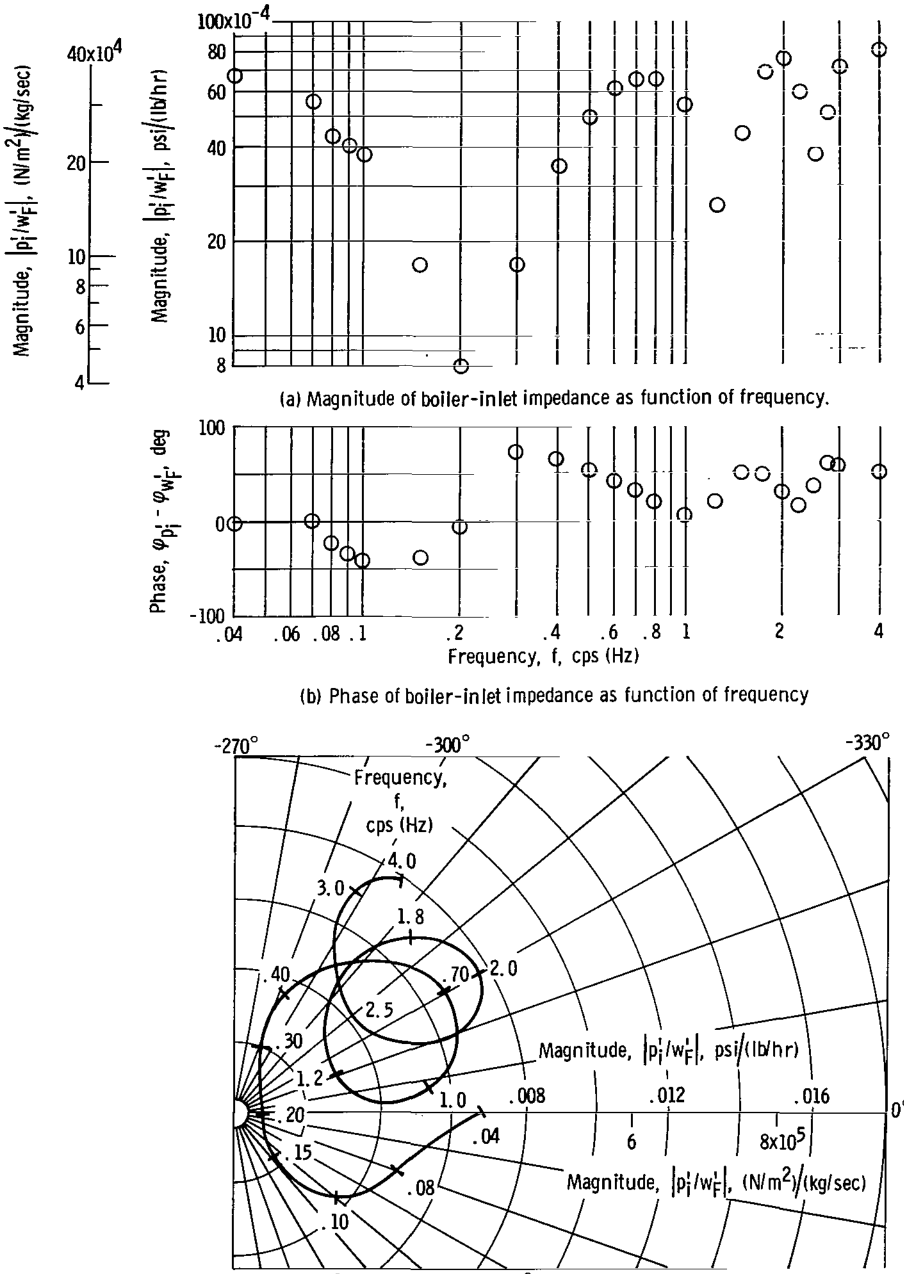


(b) Phase of boiler-inlet impedance as function of frequency.



(c) Polar plot of boiler-inlet impedance.

Figure 4. - Boiler-inlet impedance for vapor exit quality of 23 percent. Run 5.

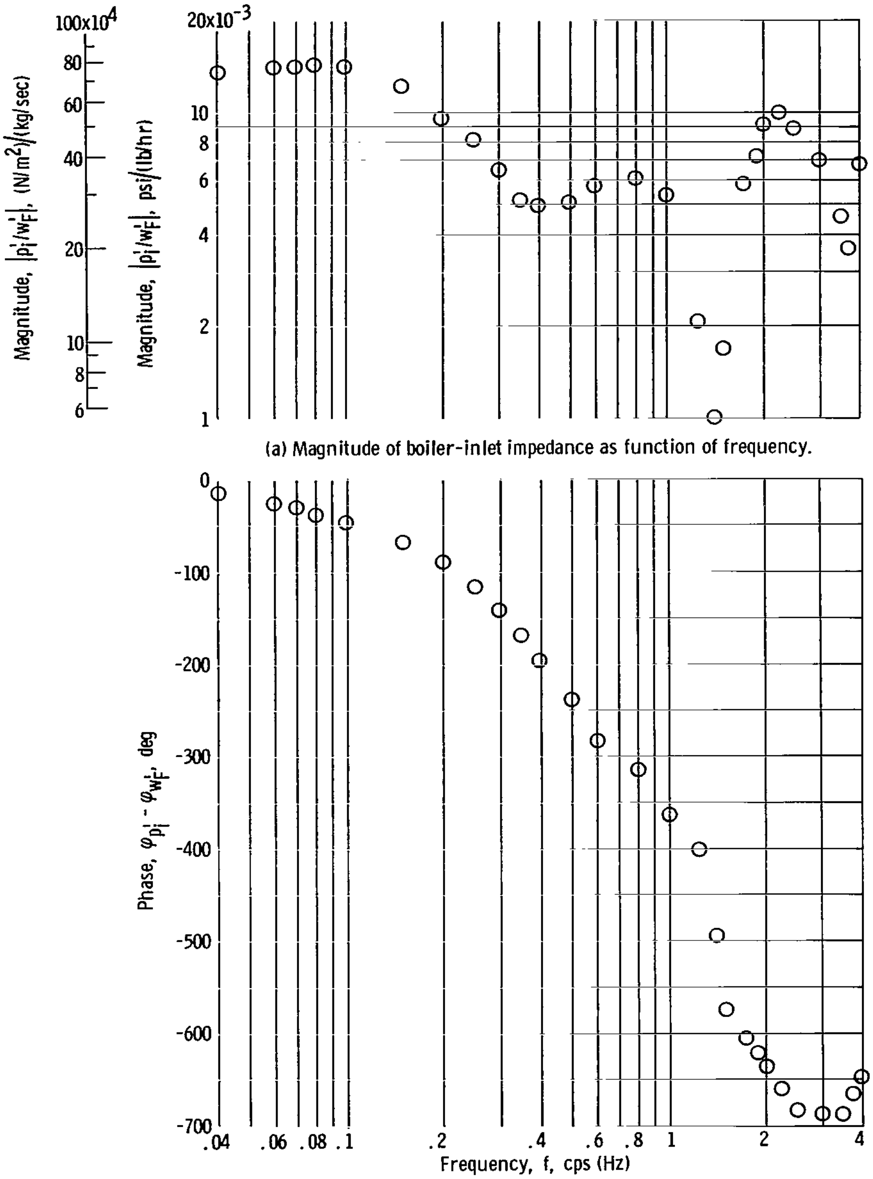


(a) Magnitude of boiler-inlet impedance as function of frequency.

(b) Phase of boiler-inlet impedance as function of frequency

(c) Polar plot of boiler-inlet impedance.

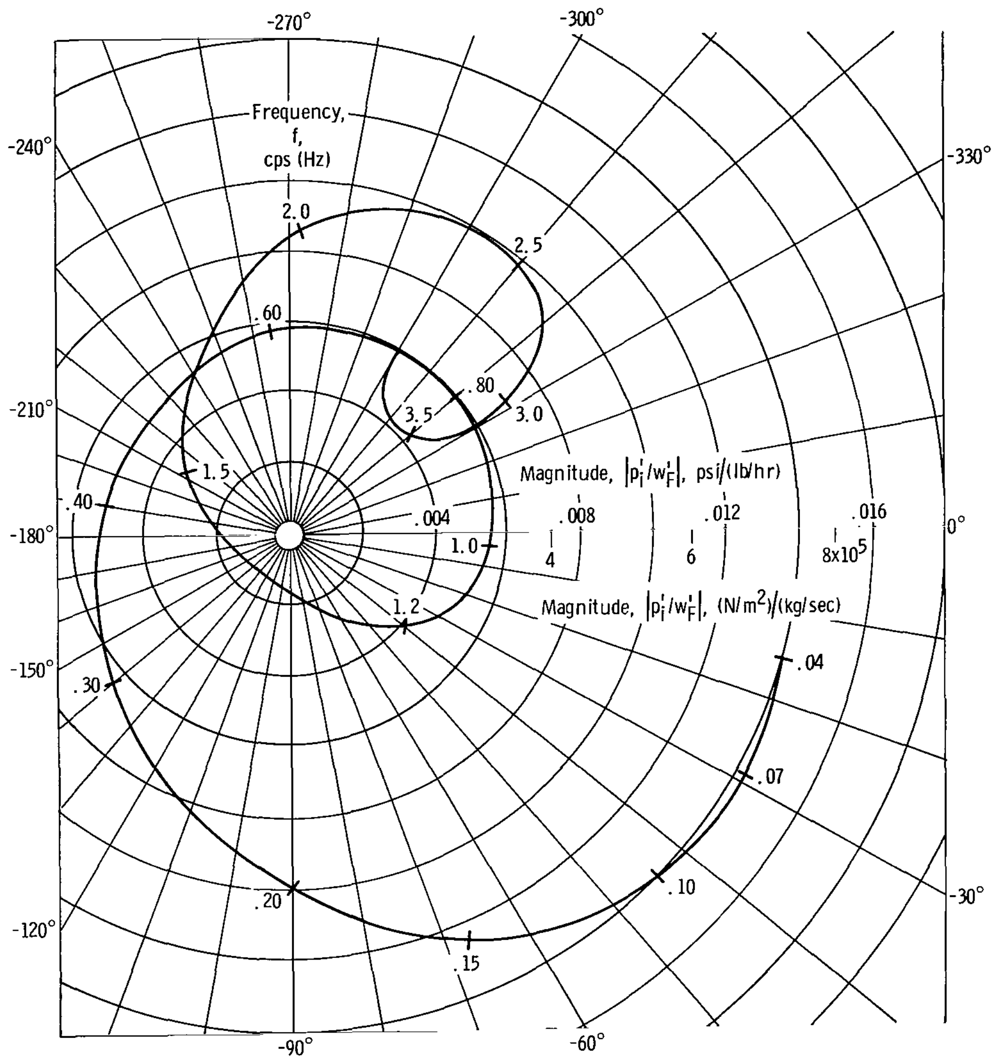
Figure 5. - Boiler-inlet impedance for exit vapor quality of 39 percent. Run 6.



(a) Magnitude of boiler-inlet impedance as function of frequency.

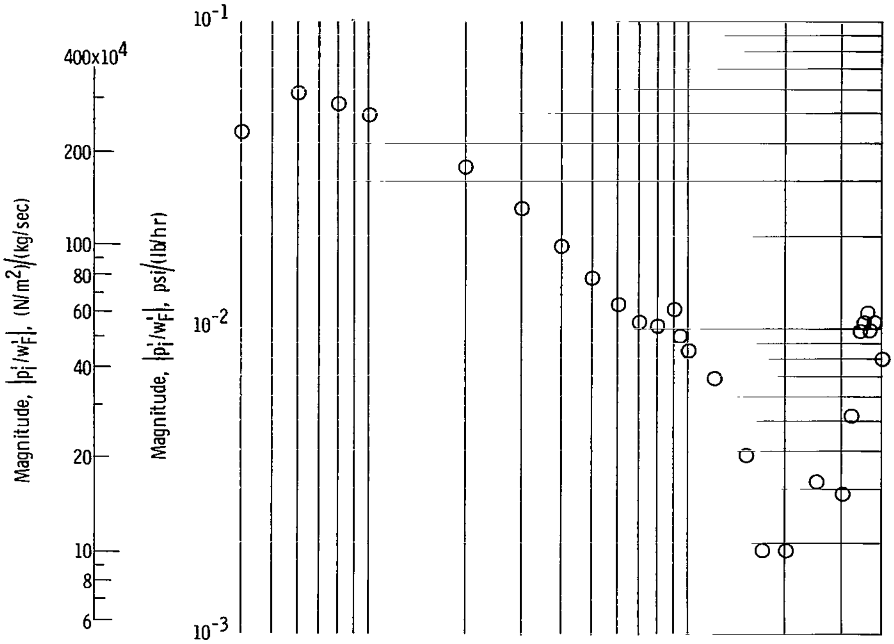
(b) Phase of boiler-inlet impedance as function of frequency.

Figure 6. - Boiler-inlet impedance for exit vapor quality of 71 percent. Run 7.

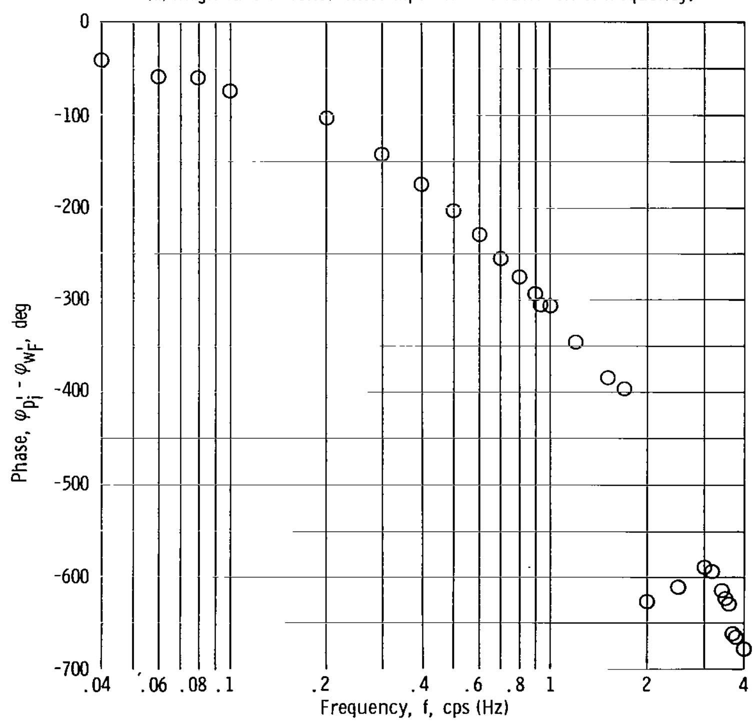


(c) Polar plot of boiler-inlet impedance.

Figure 6. - Concluded.

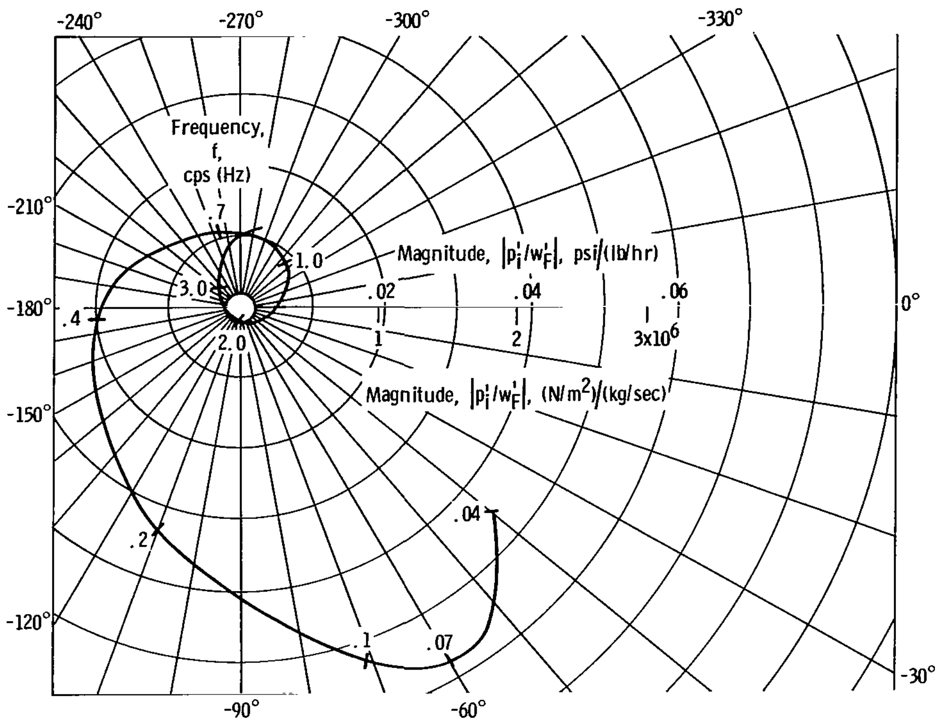


(a) Magnitude of boiler-inlet impedance as function of frequency.



(b) Phase of boiler-inlet impedance as function of frequency.

Figure 7. - Boiler-inlet impedance for exit vapor quality of 95 percent. Run 8.



(c) Polar plot of boiler-inlet impedance.

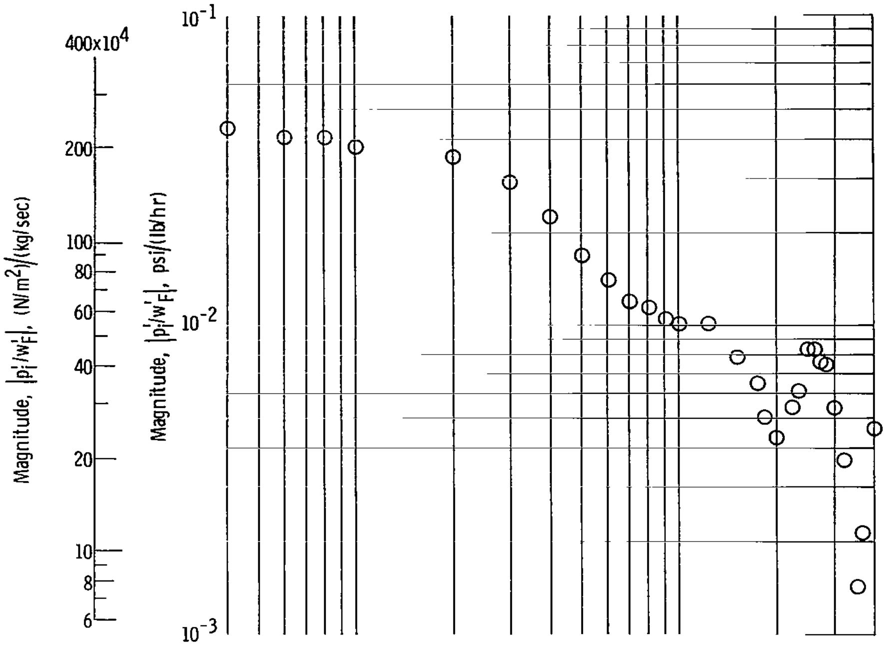
Figure 7. - Concluded.

Boiler Instability

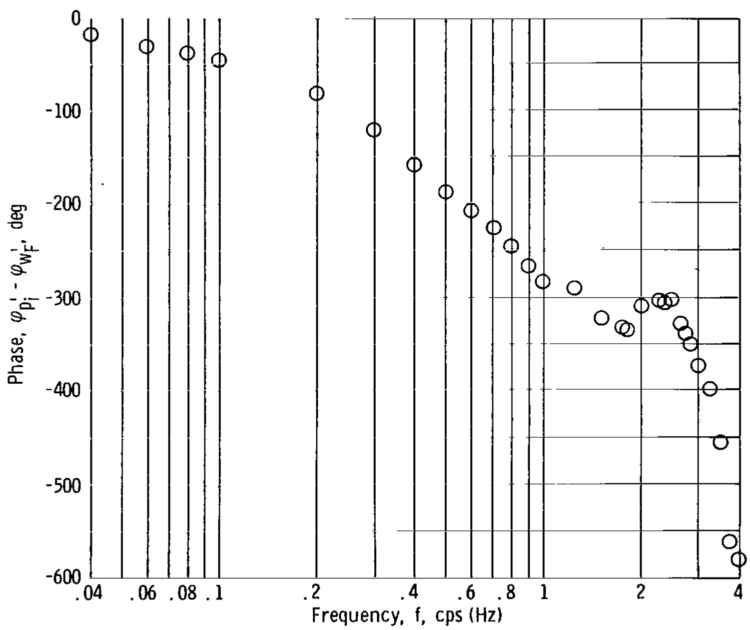
The existence of a negative impedance in figures 6 to 8 implies the possible occurrence of a hydrodynamic instability. For the boiler used in this study, operating at the same constant pressure exit conditions, a feed system coupled hydraulic instability will occur if at some frequency the feed system impedance is equal to or less than the boiler impedance and 180° out of phase with the boiler impedance.

The impedance of the feedline of the experimental apparatus reported herein was calculated by the method outlined in reference 3. The calculation showed that between 0.1 and 1.0 cps (0.1 and 1.0 Hz) the feedline impedance was approximately equal to the resistance between the accumulator and the boiler. Thus, in this frequency range, when the phase angle of the boiler impedance is near 180°, it can be assumed that the phase difference between the boiler impedance and feedline impedance is approximately 180°. Furthermore, if under these conditions, the magnitude of the boiler impedance is larger than the resistance between the accumulator and the boiler, the system will be unstable.

The validity of using frequency-response data to predict stability was determined by the natural oscillation tests described in the APPARATUS AND PROCEDURE section.

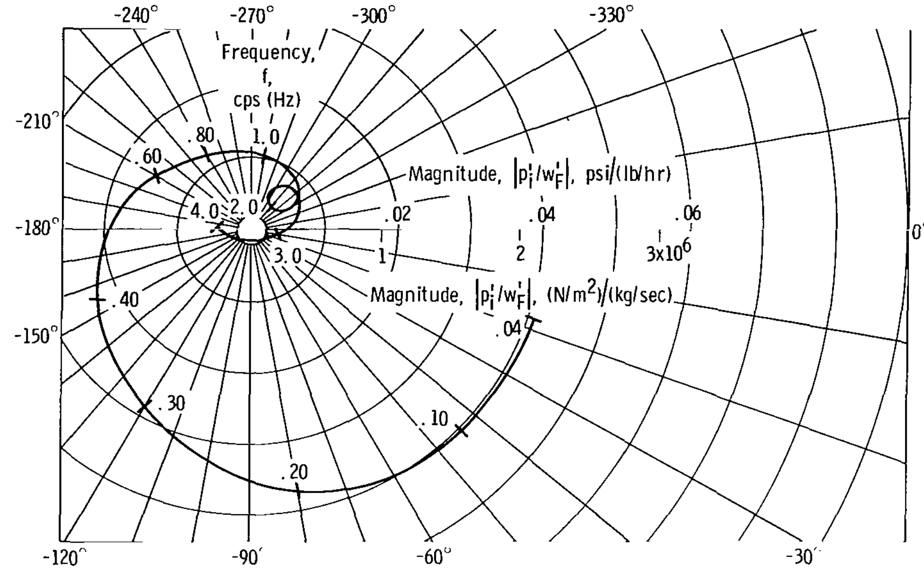


(a) Magnitude of boiler-inlet impedance as function of frequency.



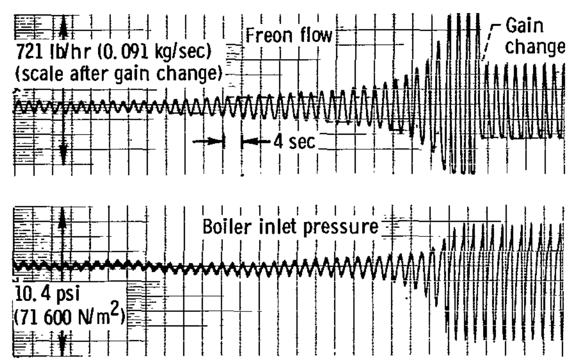
(b) Phase of boiler-inlet impedance as function of frequency.

Figure 8. - Boiler-inlet impedance for exit vapor superheat of 10° F (5.55° K). Run 9.

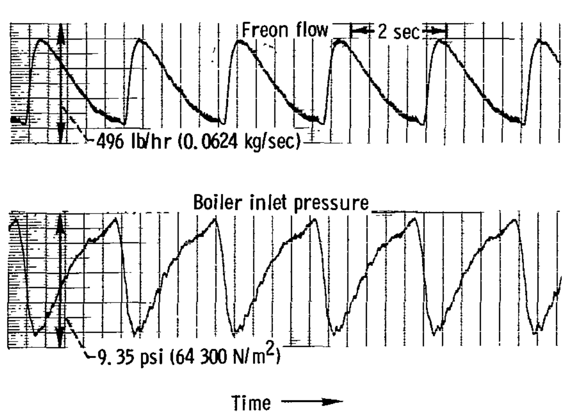


(c) Polar plot of boiler-inlet impedance.

Figure 8. - Concluded.



(a) Growth of oscillations.



(b) Oscillations after they become fully developed (expanded scale).

Figure 9. - Boiler flow and pressure oscillations that occurred at reduced feedline resistance. Run 9.

Upon decreasing the feed system resistance (by further opening the throttle valve), two of the runs listed in table I (runs 4 and 9) became unstable. For the purpose of this discussion, the results obtained from run 9 will be presented.

By opening the throttle valve to full open, the boiler became unstable, as indicated by large amplitude natural oscillations in inlet pressure and flow. Time traces of the oscillations are shown in figure 9. Figure 9(a) shows the manner in which the oscillations grow from their relatively stable steady-state values. An expanded time scale is used in figure 9(b) to show more clearly the nature of the oscillations after they become well developed. The peak-to-peak amplitude of the flow oscillations is 177 percent of the steady-state flow, and the peak-to-peak amplitude of the pressure oscillation is 39 percent of the steady-state absolute pressure. The frequency of the oscillation is 0.48 cps (0.48 Hz), and approximately a 180° phase difference exists between the pressure and the flow. The frequency and phase difference agrees with that predicted by the measurements of the boiler-inlet impedance by frequency-response techniques (fig. 8).

The other data runs of this report that gave negative values of the boiler-inlet impedance (besides the two mentioned earlier) showed no tendency to be unstable when the throttle valve was fully opened. For these runs, the magnitude of the boiler impedance at 180° was always less than the feedline resistance between the accumulator and the boiler. The magnitude of the boiler impedance at 180° can be obtained from graphs similar to those shown in figures 4 to 8. The pressure drop in the feedline between the accumulator and boiler was measured for various flow rates (with the throttle valve wide open), and the results are shown in figure 10. The feedline resistance was taken as the slope of the feedline pressure-drop - flow curve. A direct comparison between the boiler impedance at 180° and the feedline resistance for a given run can be represented

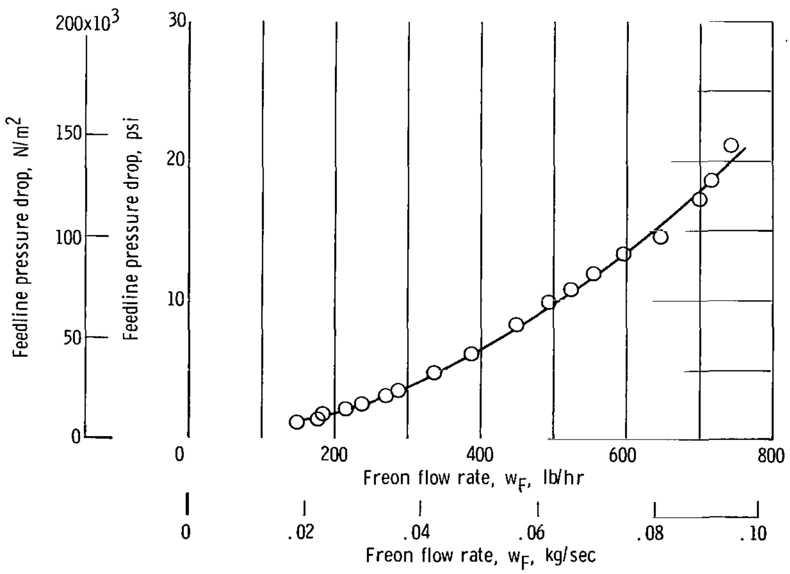


Figure 10. - Pressure drop from accumulator to boiler inlet as function of flow rate (throttle valve wide open).

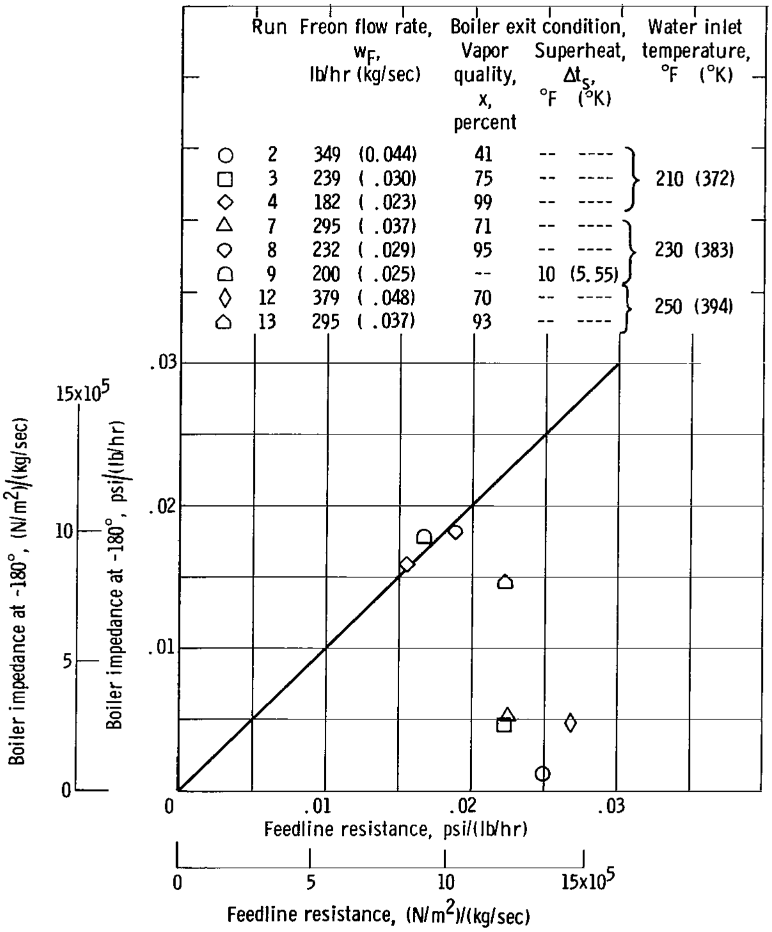


Figure 11. - Stability map for runs with negative boiler impedance.

graphically, as shown in figure 11. The figure represents a stability map; that is, if the data fall above the curve, the system is unstable. As shown in figure 11, only two runs (4 and 9) should be unstable, which agrees with the results of the test.

Therefore, by using frequency-response methods (assumption of linearity for small amplitude disturbances), it was possible to predict the value of feedline resistance necessary to make the system unstable. Thus, boiler frequency-response data and knowledge of the dynamic characteristics of the other components in the system can be used to determine if a given system will be stable.

SUMMARY OF RESULTS

The results obtained from the investigation of the frequency response of a forced-flow single-tube boiler with inserts may be summarized as follows:

1. The boiler-inlet impedance had a negative real part over some frequency range for exit vapor qualities greater than about 40 percent, including vapor superheat conditions. This implies a potentially unstable system.

2. The magnitude of the boiler inlet-impedance, below frequencies of about 1.0 cps (1.0 Hz), increased with increase in exit vapor quality.

3. The test data revealed that boiler-inlet impedance for runs with exit vapor qualities above 70 percent can be approximated by a first-order lag coupled with a pure dead time.

4. When the feedline resistance was reduced to the magnitude of the boiler-inlet impedance at 180°, the boiler went into oscillation at the frequency predicted by the frequency-response data.

5. Boiler frequency-response data and knowledge of the dynamic characteristics of the other components in the system can be used to determine if a system will be stable.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 3, 1967,
120-27-04-27-22.

APPENDIX - SYMBOLS

f	frequency, cps; Hz
L_{sc}	subcooled liquid length of boiler from beginning of heated section of boiler, in.; cm
P_i	Freon mean pressure at boiler inlet, psia; N/m^2 abs
P_o	Freon mean pressure at boiler outlet, psia; N/m^2 abs
P_i'	Freon perturbation pressure at boiler inlet, psi; N/m^2
t_{Fi}	Freon temperature at boiler inlet, ^oF; ^oK
t_{Fo}	Freon temperature at boiler outlet as measured in same diameter flow passage as boiler tube, ^oF; ^oK
t_{Fp}	Freon temperature at boiler outlet as measured in plenum tank, ^oF; ^oK
Δt_s	amount of vapor superheat at boiler outlet, ^oF; ^oK
t_{so}	Freon outlet saturation temperature corresponding to P_o, ^oF; ^oK
x	boiler outlet vapor quality, percent
w_F	Freon mean flow rate, lb/hr; kg/sec
w_w	water flow rate, lb/hr; kg/sec
w_F'	Freon perturbation flow rate, lb/hr; kg/sec
$\varphi_{P_i'}$	phase difference between boiler inlet pressure perturbation and oscillator, deg
$\varphi_{w_F'}$	phase difference between boiler inlet flow perturbation and oscillator, deg

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3. Grace, Thomas M.; and Krejsa, Eugene A.: Analytical and Experimental Study of Boiler Instabilities Due to Feed-System - Subcooled Region Coupling. NASA TN D-3961, 1967.

TABLE I. - MEAN OPERATING CONDITIONS

(a) U.S. customary units

Run	Freon							Water												Subcooled length, L_{sc}, in.
	Flow rate, w_F, lb/hr	Absolute inlet pressure, P_i, psia	Absolute outlet pressure, P_o, psia	Exit saturation temperature, t_{so}, ^oF	Temperature at boiler inlet, t_{Fi}, ^oF	Temperature at boiler outlet, t_{Fo}, ^oF	Temperature at boiler outlet measured in plenum, t_{Fp}, ^oF	Exit quality, x, percent	Flow rate, w_W, lb/hr	Temperature at station -, ^oF										
										1	2	3	4	5	6	7	8	9	10	
1	595	23.1	14.9	118.3	67	121	117	20	704	209	207	205	203	201	199	196	194	192	189	21
2	349	22.6	15.0	118.6	63	120	118	41	704	211	208	207	205	203	201	198	197	195	192	12
3	239	21.9	14.4	116.5	62	119	117	75	704	211	208	207	205	202	200	197	195	193	191	9
4	182	19.7	14.3	116.1	67	117	117	99	704	210	208	206	205	201	199	197	195	193	191	6
5	650	25.7	15.3	119.7	63	125	118	23	698	229	226	224	222	218	216	212	210	207	204	21
6	454	25.3	15.0	118.6	58	123	118	39	685	229	226	224	222	218	216	213	210	207	204	16
7	295	24.4	14.4	116.5	54	121	118	71		230	227	225	223	219	216	213	211	208	205	13
8	232	22.9	14.3	116.1	53	120	120	95		231	228	227	225	220	217	214	211	209	206	8
9	200	20.6	14.3	116.1	52	146	146	(a)		230	229	228	226	223	219	215	213	210	207	5
10	793	29.8	16.1	122.4	65	131	120	23		249	245	243	240	235	233	228	225	222	218	24
11	524	29.3	15.5	120.4	56	128	120	46		250	---	242	239	234	231	227	223	221	217	17
12	379	28.9	14.9	118.3	56	121	115	70		250	---	243	240	235	232	228	225	222	218	12
13	295	26.8	14.3	116.1	55	116	116	93		250	---	244	240	237	233	229	226	223	219	9

(b) SI units

Run	Freon							Water												Subcooled length, L_{sc}, cm
	Flow rate, w_F, kg/sec	Absolute inlet pressure, P_i, N/m^2 abs	Absolute outlet pressure, P_o, N/m^2 abs	Exit saturation temperature, t_{so}, ^oK	Temperature at boiler inlet, t_{Fi}, ^oK	Temperature at boiler outlet, t_{Fo}, ^oK	Temperature at boiler outlet measured in plenum, t_{Fp}, ^oK	Exit quality, x, percent	Flow rate, w_W, kg/sec	Temperature at station -, ^oK										
										1	2	3	4	5	6	7	8	9	10	
1	0.075	159 000	103 000	321.3	292	322	320	20	0.089	371	370	369	368	367	366	364	363	362	360	53.3
2	.044	156 000	103 000	321.4	290	322	321	41		372	371	370	369	368	367	365	365	363	362	30.5
3	.030	151 000	99 000	320.3	290	321	320	75		372	371	370	369	367	366	365	363	362	361	22.8
4	.023	136 000	99 000	320.1	292	321	321	99		372	371	370	369	367	366	365	363	362	361	15.2
5	.082	177 000	105 000	322.1	290	325	321	23	.088	382	381	380	378	376	375	373	372	370	368	53.3
6	.057	174 000	103 000	321.4	287	323	321	39	.086	382	381	380	378	376	375	373	372	370	368	40.6
7	.037	168 000	99 000	320.3	285	322	321	71		383	381	380	379	377	375	373	372	371	369	33.0
8	.029	158 000	99 000	320.1	285	322	327	95		383	382	381	380	377	376	374	372	371	370	20.3
9	.025	142 000	99 000	320.1	284	336	336	(b)		383	382	382	381	379	377	375	373	372	370	12.7
10	.099	205 000	111 000	323.6	291	328	322	23		393	391	390	388	386	385	382	380	378	376	61.0
11	.066	202 000	107 000	322.4	286	326	322	46		394	---	390	388	385	383	381	379	378	376	43.2
12	.048	199 000	103 000	321.3	286	322	319	70		394	---	390	388	386	384	382	380	378	376	30.5
13	.037	185 000	99 000	320.1	286	320	320	73		394	---	391	388	387	385	382	381	379	377	22.8

[a]Superheat, 10^o F.
[b]Superheat, 5.55^o K.

TABLE II. - BOILER PERTURBATION DATA

(a) Run 1; boiler-outlet condition, 20-percent quality; Freon flow rate, 595 pounds per hour (0.075 kg/sec); inlet water temperature, 209° F (371° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w_F' \rvert$		Phase relative to oscillator, w_F', deg	Magnitude,[a] $\lvert P_i' \rvert$		Phase relative to oscillator, $\varphi_{p_i'}$, deg	Magnitude, $\lvert P_i'/w_F' \rvert$		Phase, $\varphi_{p_i'} - \varphi_{w_F'}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	64	0.0080	-12	0.28	1930	-7	0.0044	24.1×10^4	5
.06	66	.0083	-15	.33	2280	-7	.0050	27.4	8
.08	70	.0088	-15	.29	2000	-17	.0042	23.0	-2
.10	66	.0083	-17	.25	1720	-20	.0038	20.8	-3
.15	66	.0083	-17	.23	1590	-10	.0035	19.2	7
.20	68	.0085	-21	.25	1720	-6	.0037	20.3	15
.30	64	.0080	-24	.28	1930	-2	.0044	24.1	22
.40	66	.0083	-24	.35	2410	0	.0053	29.1	24
.50	59	.0074	-26	.36	2480	-3	.0061	33.4	23
.60	57	.0072	-33	.39	2690	-12	.0068	37.3	21
.70	57	.0072	-32	.36	2480	-13	.0063	34.6	19
.80	54	.0068	-27	.35	2410	-17	.0065	35.6	10
1.0	58	.0073	-29	.31	2140	-23	.0053	29.1	6
1.1	57	.0072	-29	.29	2000	-19	.0051	28.0	10
1.25	57	.0072	-32	.27	1860	-13	.0047	25.8	19
1.4	56	.0070	-32	.29	2000	-2	.0052	28.5	30
1.5	54	.0068	-32	.30	2070	0	.0055	30.2	32
1.7	56	.0070	-34	.36	2480	1	.0064	35.1	33
2.0	56	.0070	-38	.39	2690	-7	.0070	38.4	31
2.2	55	.0069	-37	.37	2550	-8	.0067	36.7	29
2.4	55	.0069	-39	.34	2440	-6	.0062	34.0	33
2.5	56	.0070	-40	.34	2440	-3	.0061	33.4	37
3.0	57	.0072	-46	.43	2960	2	.0075	41.1	44
4.0	57	.0072	-53	.47	3240	-2	.0082	45.0	51

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(b) Run 2; boiler-outlet condition, 41-percent quality; Freon flow rate, 349 pounds per hour (0.044 kg/sec); inlet water temperature, 211° F (372° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w_F' \rvert$		Phase relative to oscillator, w_F', deg	Magnitude,[a] $\lvert P_i' \rvert$		Phase relative to oscillator, $\varphi_{P_i'}$, deg	Magnitude, $\lvert P_i'/w_F' \rvert$		Phase, $\varphi_{P_i'} - \varphi_{w_F'}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.04	40	0.0050	-17	0.24	1650	-22	0.006	32.9×10^4	-5
.06	40	.0050	-18	.23	1580	-27	.0057	31.3	-9
.08	40	.0050	-18	.21	1450	-51	.0052	28.5	-33
.10	37	.0047	-17	.17	1170	-67	.0046	25.2	-50
.15	35	.0044	-21	.10	690	-102	.0029	15.9	-81
.20	37	.0047	-22	.06	410	-144	.0016	8.8	-122
.25	37	.0047	-27	.05	340	-208	.0013	7.1	-181
.30	36	.0045	-31	.07	480	-259	.0019	10.4	-228
.40	34	.0043	-36	.13	900	-305	.0038	20.8	-269
.50	33	.0041	-33	.17	1170	-334	.0051	28.0	-303
.60	29	.0036	-40	.18	1240	-367	.0062	34.0	-327
.80	27	.0034	-38	.16	1100	-383	.0059	32.4	-345
1.0	31	.0039	-36	.13	900	-397	.0042	23.0	-361
1.1	28	.0035	-39	.07	480	-404	.0025	13.7	-365
1.2	↓	↓	-40	.04	280	-392	.0014	7.7	-352
1.25	↓	↓	-43	.03	210	-370	.0011	6.0	-327
1.30	↓	↓	-42	.04	280	-347	.0014	7.7	-305
1.40	↓	↓	-43	.07	480	-324	.0025	13.7	-281
1.50	31	.0039	-45	.11	760	-323	.0035	19.2	-278
1.60	28	.0035	-48	.15	1030	-330	.0054	29.6	-282
1.75	26	.0033	-51	.17	1170	-347	.0065	35.6	-296
1.80	26	.0033	-50	.18	1240	-348	.0069	37.8	-298
1.90	26	.0033	-50	.19	1310	-357	.0073	40.1	-307
1.95	25	.0031	-52	.19	1310	-362	.0076	41.6	-310
1.99	25	.0031	-54	.19	1310	-366	.0076	41.6	-312
2.00	30	.0038	-46	.23	1580	-366	.0077	42.2	-320
2.20	28	.0035	-52	.19	1310	-379	.0068	37.3	-327
2.40	28	.0035	-53	.16	1100	-384	.0057	31.3	-331
3.00	26	.0033	-58	.14	960	-372	.0054	29.6	-314
4.00	30	.0038	-71	.21	1450	-372	.0070	38.4	-301

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(c) Run 3; boiler-outlet condition, 75-percent quality; Freon flow rate, 239 pounds per hour (0.030 kg/sec); inlet water temperature, 211° F (372° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\lvert P'_i \rvert$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\lvert P'_i/w'_F \rvert$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m²		psi/(lb/hr)	(N/m²)/(kg/sec)	
0.04	22	0.0028	-10	0.34	2340	-20	0.0155	85.0×10⁴	-10
.06	21	.0026	-12	.31	2140	-40	.0147	80.5	-28
.08	21	.0026	-10	.30	2070	-48	.0143	78.5	-38
.10	22	.0028	-10	.29	2000	-58	.0132	72.4	-48
.15	24	.0030	-10	.29	2000	-79	.0121	66.4	-69
.20	27	.0034	-10	.25	1720	-107	.0092	50.4	-97
.25	27	.0034	-16	.22	1520	-135	.0081	44.4	-119
.30	30	.0038	-23	.18	1240	-169	.0060	32.9	-146
.35	29	.0036	-28	.14	960	-200	.0048	26.3	-172
.40	29	.0036	-35	.13	900	-240	.0045	24.6	-205
.50	26	.0033	-40	.12	830	-296	.0046	25.2	-256
.60	24	.0030	-43	.14	960	-330	.0058	31.8	-287
.70	23	.0029	-43	.14	960	-353	.0061	33.4	-310
.80	21	.0026	-43	.13	900	-372	.0062	34.0	-329
.90	21	.0026	-42	.12	830	-397	.0057	31.3	-355
1.0	21	.0026	-38	.11	760	-406	.0052	28.5	-368
1.1	22	.0028	-42	.09	620	-417	.0041	22.5	-375
1.25	21	.0026	-46	.05	410	-441	.0024	13.1	-395
1.38	23	.0029	-50	.02	140	-469	.0009	4.9	-419
1.50	23	.0029	-50	.016	1100	-630	.0009	38.4	-580
1.75	23	.0029	-58	.07	480	-679	.0030	16.4	-621
2.0	21	.0026	-59	.10	690	-705	.0048	26.3	-646
2.2	21	.0026	-64	.11	760	-707	.0052	28.5	-643
2.5	20	.0025	-69	.14	960	-721	.0070	38.4	-652
2.75	18	.0023	-72	.14	960	-742	.0078	42.7	-670
2.9	18	.0023	-71	.13	900	-752	.0072	39.4	-681
3.0	20	.0025	-68	.09	620	-761	.0045	24.6	-693
3.1	20	.0025	-73	.10	690	-763	.0050	27.4	-690
3.25	19	.0024	-76	.07	480	-760	.0037	20.3	-684
3.50	20	.0025	-81	.07	480	-742	.0035	19.2	-661
3.75	19	.0024	-86	.09	620	-735	.0047	25.8	-649
4.00	20	.0025	-85	.11	760	-738	.0055	30.2	-653

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(d) Run 4; boiler-outlet condition, 99-percent quality; Freon flow rate, 182 pounds per hour (0.023 kg/sec); inlet water temperature, 210° F (372° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\lvert P'_i \rvert$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\lvert P'_i/w'_F \rvert$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	4	0.0005	-14	0.24	1650	-35	0.060	32.9×10^5	-21
.05	4	.0005	-21	.21	1450	-41	.052	28.5	-20
.07	4	.0005	-10	.18	1240	-54	.045	24.7	-44
.08	5	.0006	-6	.19	1310	-53	.038	20.8	-47
.10	4	.0005	-16	.20	1380	-57	.060	32.9	-41
.12	5	.0006	-3	.18	1240	-77	.036	19.7	-74
.15	5	.0006	-2	.18	1240	-84	.036	19.7	-82
.20	7	.0009	-2	.20	1380	-109	.029	15.9	-107
.25	10	.0013	-5	.22	1520	-136	.022	12.1	-131
.30	15	.0019	-22	.26	1790	-177	.017	9.3	-155
.33	14	.0018	-37	.24	1650	-204	.017	9.3	-167
.34	14	.0018	-42	.22	1520	-212	.016	8.7	-170
.35	14	.0018	-44	.22	1520	-223	.016	8.7	-179
.40	15	.0019	-46	.20	1380	-228	.013	7.1	-182
.50	14	.0018	-77	.12	830	-295	.008	4.4	-218
.60	14	.0018	-48	.11	760	-324	.008	4.4	-276
.80	11	.0013	-48	.11	760	-359	.010	5.5	-311
.90	6	.0008	-60	.05	340	-399	.008	4.4	-339
1.0	6	.0008	-63	.05	340	-418	.008	4.4	-355
1.1	7	.0009	-61	.04	280	-435	.006	3.3	-374
1.2			-63	.03	210	-453	.004	2.2	-390
1.3			-66	.02	140	-471	.003	1.6	-405
1.4			-72	.01	70	-497	.001	.5	-425
1.6			-78	.01	70	-645	.001	.5	-567
1.8			-83	.02	140	-710	.003	1.6	-627
2.0			-85	.02	140	-748	.003	1.6	-663
2.2	6	.0008	-90	.01	70	-755	.002	1.1	-665
2.3			-93	.01	70	-695	.002	1.1	-602
2.4			-96	.02	140	-700	.003	1.6	-604
2.5			-102	.03	210	-696	.005	2.7	-594
2.6			-102	.04	280	-730	.007	3.8	-628
2.7	5	.0006	-105	.04	280	-730	.008	4.4	-625
2.8			-105	.04	280	-750	.008	4.4	-645
3.0			-105	.04	280	-770	.008	4.4	-665
3.5			-110	.02	140	-794	.004	2.2	-684
4.0			-122	.02	140	-770	.004	2.2	-648

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(e) Run 5; boiler-outlet condition, 23-percent quality; Freon flow rate, 650 pounds per hour (0.082 kg/sec); inlet water temperature, 229° F (382° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\lvert P'_i \rvert$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\lvert P'_i/w'_F \rvert$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	84	0.0105	-11	0.34	2340	-4	0.0041	22.5×10^6	7
.05	81	.0102	-16	.38	2620	-10	.0047	25.8	6
.06	78	.0098	-16	.38	2620	-14	.0049	26.9	2
.08	76	.0095	-18	.32	2200	-19	.0042	23.0	-1
.09	65	.0082	-17	.26	1790	-22	.0040	21.9	-5
.10	63	.0079	-18	.19	1310	-20	.0030	16.5	-2
.15	67	.0084	-19	.17	1170	3	.0025	13.7	22
.20	62	.0078	-21	.23	1590	15	.0037	20.3	36
.30	67	.0084	-24	.33	2270	12	.0049	26.9	36
.40	62	.0078	-26	.35	2410	8	.0057	31.2	34
.60	24	.0030	-54	.17	1170	-24	.0071	38.9	30
.80	60	.0075	-32	.48	3310	-11	.0080	43.8	21
1.0	60	.0075	-30	.44	3030	-20	.0073	40.0	10
1.25	58	.0073	-37	.36	2480	-21	.0062	34.0	16
1.50	56	.0070	-37	.33	2270	-7	.0059	32.4	30
1.75	56	.0070	-40	.37	2550	-4	.0066	36.2	36
2.0	59	.0074	-39	.43	2960	-5	.0073	40.0	34
2.5	54	.0068	-42	.39	2690	-8	.0072	39.5	34
2.75	53	.0064	-45	.37	2550	-1	.0070	38.4	44
3.0	54	.0068	-46	.45	3100	5	.0083	45.5	51
4.0	53	.0064	-53	.52	3580	-4	.0098	53.7	49

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(f) Run 6; boiler-outlet condition, 39-percent quality; Freon flow rate, 454 pounds per hour (0.057 kg/sec); inlet water temperature, 229° F (382° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\lvert P'_i \rvert$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\lvert P'_i/w'_F \rvert$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m²		psi/(lb/hr)	(N/m²)/(kg/sec)	
0.04	71	0.0089	-10	0.49	3370	-11	0.0069	37.8×10^4	-1
.07	65	.0082	-15	.37	2550	-14	.0057	31.3	1
.08	52	.0065	-14	.23	1580	-35	.0044	24.1	-21
.09	51	.0064	-14	.21	1450	-48	.0041	22.5	-34
.10	52	.0065	-15	.20	1380	-56	.0038	20.8	-41
.15	53	.0066	-16	.09	620	-55	.0017	9.3	-39
.20	53	.0066	-19	.04	280	-26	.0008	4.4	-7
.30	53	.0066	-23	.09	620	50	.0017	9.3	73
.40	51	.0064	-26	.18	1240	40	.0035	19.2	66
.50	50	.0063	-29	.25	1720	26	.0050	27.4	55
.60	47	.0059	-30	.29	1930	12	.0062	34.0	42
.70	46	.0058	-30	.31	2140	1	.0067	36.7	31
.80	45	.0057	-30	.30	2070	-10	.0067	36.7	20
1.0	44	.0055	-30	.24	1650	-24	.0055	30.2	6
1.25	43	.0054	-35	.11	760	-15	.0026	14.2	20
1.50	43	.0054	-35	.19	1310	15	.0044	24.1	50
1.75	42	.0053	-39	.29	1930	10	.0069	37.8	49
2.00	41	.0052	-39	.31	2140	-10	.0076	41.6	29
2.25	41	.0052	-40	.24	1650	-24	.0059	32.3	16
2.50	42	.0053	-42	.16	1100	-7	.0038	20.8	35
2.75	41	.0052	-47	.21	1450	14	.0051	27.9	61
3.0	42	.0053	-50	.30	2070	9	.0072	39.5	59
4.0	41	.0052	-57	.33	2270	-7	.0081	44.3	50

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(g) Run 7; boiler-outlet condition, 71-percent quality; Freon flow rate, 295 pounds per hour (0.037 kg/sec); inlet water temperature, 230° F (383° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\|w'_F\|$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\|P'_i\|$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\|P'_i/w'_F\|$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.04	30	0.0038	-11	0.41	2820	-25	0.0137	75.0×10^4	-14
.06	31	.0039	-11	.44	3030	-34	.0142	77.9	-23
.07	32	.0040	-10	.46	3170	-38	.0144	79.0	-28
.08	31	.0039	-10	.45	3100	-47	.0145	79.5	-37
.10	31	.0039	-10	.44	3030	-55	.0142	77.9	-45
.15	33	.0041	-10	.41	2820	-76	.0124	68.0	-66
.20	37	.0046	-11	.36	2480	-99	.0097	53.2	-88
.25	39	.0049	-14	.32	2200	-128	.0082	45.0	-114
.30	40	.0050	-19	.26	1790	-159	.0065	35.6	-140
.35	40	.0050	-25	.21	1450	-193	.0052	28.5	-168
.40	38	.0048	-32	.19	1310	-226	.0050	27.4	-194
.50	35	.0045	-38	.18	1270	-275	.0051	29.2	-237
.60	31	.0039	-40	.18	1240	-322	.0058	31.8	-282
.80	28	.0035	-40	.17	1170	-353	.0061	33.4	-313
1.0	28	.0035	-37	.15	1030	-399	.0054	29.6	-362
1.25	29	.0036	-42	.06	410	-442	.0021	11.5	-400
1.40	30	.0038	-49	.03	210	-543	.0010	5.5	-494
1.50	30	.0038	-45	.05	340	-617	.0017	9.3	-572
1.75	29	.0036	-55	.17	1170	-657	.0059	32.4	-602
1.90	28	.0035	-63	.20	1380	-683	.0072	39.5	-620
2.00	26	.0033	-58	.24	1650	-693	.0092	50.5	-635
2.25	24	.0030	-68	.24	1650	-727	.0100	54.8	-659
2.50	24	.0030	-64	.21	1450	-746	.0088	48.2	-682
3.00	23	.0029	-70	.16	1100	-754	.0070	38.4	-684
3.50	24	.0030	-75	.11	760	-760	.0046	25.2	-685
3.75	25	.0031	-80	.09	620	-743	.0036	19.7	-663
4.00	25	.0031	-79	.17	1170	-725	.0068	37.3	-646

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(h) Run 8; boiler-outlet condition, 95-percent quality; Freon flow rate, 232 pounds per hour (0.029 kg/sec); inlet water temperature, 231° F (383° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet: Magnitude,[a] $\lvert w_F' \rvert$, lb/hr	kg/sec	Phase relative to oscillator, w_F', deg	Perturbation data for pressure at boiler inlet: Magnitude,[a] $\lvert P_i' \rvert$, psi	N/m^2	Phase relative to oscillator, $\varphi_{p_i'}$, deg	Boiler-inlet impedance: Magnitude, $\lvert P_i'/w_F' \rvert$, psi/(lb/hr)	$(N/m^2)/(kg/sec)$	Phase, $\varphi_{p_i'} - \varphi_{w_F'}$, deg
0.04	4.3	0.00054	-20	0.19	1310	-59	0.0442	24.3×10^5	-39
.06	3.1	.00039	-3	.18	1240	-59	.0581	31.9	-57
.08	3.3	.00041	-1	.18	1240	-61	.0545	29.9	-60
.10	3.4	.00043	0	.17	1170	-72	.0500	27.4	-72
.20	5.0	.00063	-1	.17	1170	-104	.0340	18.6	-103
.30	8.8	.00110	-17	.22	1520	-158	.0250	13.7	-141
.40	9.5	.00126	-57	.18	1240	-231	.0190	10.4	-174
.50	7.4	.00093	-79	.11	760	-283	.0149	8.2	-204
.60	5.8	.00073	-90	.07	480	-319	.0121	6.6	-229
.70	13.2	.00166	-65	.14	960	-319	.0106	5.8	-254
.80	11.6	.00146	-66	.12	830	-341	.0103	5.6	-275
.90	4.3	.00054	-90	.05	340	-382	.0117	6.4	-292
.95	10.5	.00132	-66	.10	700	-370	.0095	5.2	-304
1.0	4.7	.00059	-90	.04	280	-397	.0085	4.7	-307
1.2	10.1	.00127	-62	.07	480	-408	.0069	3.8	-346
1.5	10.3	.00129	-63	.04	280	-446	.0039	2.1	-383
1.7	10.5	.00132	-66	.02	140	-461	.0019	1.1	-395
2.0	10.3	.00129	-76	.02	140	-704	.0019	1.1	-628
2.5	9.2	.00116	-83	.03	210	-693	.0032	1.8	-610
3.0	10.2	.00128	-94	.03	210	-681	.0029	1.6	-587
3.2	9.7	.00122	-99	.05	340	-692	.0052	2.9	-593
3.4	9.1	.00114	-105	.09	620	-720	.0099	5.4	-615
3.5	8.6	.00108	-106	.09	620	-727	.0105	5.8	-621
3.6	7.9	.00099	-107	.09	620	-734	.0114	6.2	-627
3.7	8.1	.00102	-104	.08	550	-765	.0099	5.4	-661
3.8	7.6	.00095	-106	.08	550	-769	.0105	5.8	-663
4.0	2.5	.00031	-146	.02	140	-824	.0080	4.4	-678

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(i) Run 9; boiler-outlet condition, 10° F (5.55° K) superheat; Freon flow rate, 200 pounds per hour (0.025 kg/sec); inlet water temperature, 230° F (383° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w_F' \rvert$		Phase relative to oscillator, w_F', deg	Magnitude,[a] $\lvert P_i' \rvert$		Phase relative to oscillator, $\varphi_{P_i'}$, deg	Magnitude, $\lvert P_i'/w_F \rvert$		Phase, $\varphi_{P_i'} - \varphi_{w_F'}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	13	0.0016	-11	0.57	3930	-28	0.0438	24.0×10^5	-17
.06	14	.0018	-6	.57	3930	-35	.0407	22.3	-29
.08	14	.0018	-3	.57	3930	-39	.0407	22.3	-36
.10	15	.0019	3	.57	3930	-40	.0380	20.8	-43
.20	18	.0023	14	.63	4340	-66	.0350	19.2	-80
.30	30	.0038	22	.87	6000	-98	.0290	15.9	-120
.40	54	.0068	-8	1.21	830	-165	.0224	12.3	-157
.50	44	.0055	-42	.74	5100	-228	.0168	9.2	-186
.60	33	.0041	-54	.46	3170	-262	.0139	7.6	-208
.70	27	.0034	-58	.32	2210	-284	.0119	6.5	-226
.80	22	.0028	-60	.25	1720	-305	.0114	6.2	-245
.90	20	.0025	-60	.21	1450	-325	.0105	5.7	-265
1.0	18	.0023	-57	.18	1240	-339	.0100	5.5	-282
1.25	15	.0019	-65	.15	1030	-353	.0100	5.5	-288
1.50	14	.0018	-61	.11	760	-383	.0078	4.3	-322
1.75	14	.0018	-65	.09	620	-396	.0064	3.5	-331
1.85	14	.0018	-65	.07	480	-398	.0050	2.7	-333
2.00	14	.0018	-69	.06	410	-378	.0043	2.4	-309
2.25	13	.0016	-73	.07	480	-375	.0054	3.0	-302
2.35	13	.0016	-75	.08	550	-381	.0061	3.3	-306
2.50	12	.0015	-74	.10	700	-375	.0083	4.5	-301
2.65	12	.0015	-75	.10	700	-402	.0083	4.5	-327
2.75	12	.0015	-74	.09	620	-411	.0075	4.1	-337
2.85	12	.0015	-75	.09	620	-424	.0075	4.1	-349
3.00	13	.0016	-75	.07	480	-445	.0054	3.0	-370
3.25	14	.0018	-79	.05	340	-475	.0036	2.0	-396
3.50	14	.0018	-83	.02	140	-536	.0014	.8	-453
3.75	14	.0018	-92	.03	210	-652	.0021	1.1	-560
4.00	13	.0016	-101	.06	410	-681	.0046	2.5	-580

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(j) Run 10; boiler-outlet condition, 23-percent quality; Freon flow rate, 793 pounds per hour (0.099 kg/sec); inlet water temperature, 249° F (393° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\lvert P'_i \rvert$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\lvert P'_i/w'_F \rvert$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m²		psi/(lb/hr)	(N/m²)/(kg/sec)	
0.04	56	0.0070	-18	0.20	1380	2	0.0036	19.7×10⁴	20
.06	57	.0072	-19	.21	1450	2	.0037	20.3	21
.08	57	.0072	-20	.24	1650	-4	.0042	23.0	16
.10	57	.0072	-22	.24	1650	-11	.0042	23.0	11
.15	55	.0069	-25	.20	1380	-1	.0036	19.7	24
.20	56	.0070	-26	.24	1650	5	.0043	23.6	31
.30	55	.0069	-29	.31	2140	3	.0056	30.7	32
.40	54	.0068	-33	.36	2480	-1	.0067	36.7	32
.50	48	.0060	-36	.39	2680	-5	.0081	44.3	31
.60	47	.0059	-36	.42	3890	-8	.0089	48.8	28
.70	45	.0057	-37	.43	3960	-14	.0096	52.6	23
.80	45	.0057	-37	.42	3890	-20	.0093	51.0	17
.90	45	.0057	-37	.41	2820	-22	.0091	49.8	15
1.0	45	.0057	-38	.40	2750	-25	.0089	48.8	13
1.25	42	.0053	-40	.32	2200	-29	.0076	41.6	11
1.50	42	.0053	-40	.29	1990	-21	.0069	37.8	19
1.75	41	.0051	-44	.30	2070	-17	.0073	40.0	27
2.00	43	.0054	-45	.38	2620	-14	.0088	48.2	31
2.25	40	.0050	-49	.35	2410	-18	.0087	47.6	31
2.50	40	.0050	-49	.36	2480	-20	.0090	49.3	29
2.75	40	.0050	-52	.32	2200	-20	.0080	43.8	32
3.00	42	.0053	-54	.35	2410	-14	.0083	45.5	40
3.25	39	.0049	-58	.38	2620	-13	.0097	53.1	45
3.50	38	.0048	-58	.42	3890	-14	.0110	60.3	44
3.75	38	.0048	-62	.42	3890	-22	.0110	60.3	40
4.00	40	.0050	-60	.41	2820	-22	.0103	56.5	38

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(k) Run 11; boiler-outlet condition, 46-percent quality; Freon flow rate, 524 pounds per hour (0.066 kg/sec); inlet water temperature, 250° F (394° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\|w'_F\|$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\|P'_i\|$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\|P'_i/w'_F\|$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	44	0.0055	-15	0.22	1520	-18	0.0050	27.4×10^4	-3
.06	44	.0055	-15	.22	1520	-28	.0050	27.4	-13
.08	44	.0055	-16	.21	1450	-40	.0048	26.3	-24
.10	43	.0054	-18	.16	1100	-53	.0037	20.3	-35
.125	39	.0049	-22	.10	700	-65	.0026	14.2	-43
.20	39	.0049	-25	.03	210	-44	.0008	4.4	-19
.30	39	.0049	-30	.07	480	29	.0018	9.9	59
.40	38	.0048	-33	.12	830	31	.0032	17.5	64
.50	35	.0044	-38	.18	1240	25	.0051	28.0	63
.60	33	.0041	-40	.22	1520	11	.0067	36.7	51
.70	32	.0040	-40	.22	1520	0	.0069	37.8	40
.80	30	.0038	-41	.23	1580	-10	.0077	42.2	31
.90			-41	.22	1520	-19	.0073	40.0	22
1.0			-40	.20	1380	-25	.0067	36.7	15
1.25			-43	.14	960	-35	.0047	25.7	8
1.55			-46	.14	960	-8	.0047	25.7	38
1.75	29	.0036	-51	.18	1240	-3	.0062	34.0	48
2.00	28	.0035	-50	.22	1520	-13	.0079	43.3	37
2.25	28	.0035	-51	.21	1450	-30	.0075	41.0	21
2.50	29	.0036	-51	.16	1100	-36	.0055	30.1	15
2.75	28	.0035	-55	.12	830	-23	.0043	23.6	32
3.00			-58	.15	1030	-1	.0054	29.6	57
3.25			-61	.19	1310	-4	.0068	37.2	57
3.50			-62	.20	1380	-8	.0071	38.9	54
3.75			-66	.20	1380	-10	.0071	38.9	56
4.00	26	.0033	-69	.22	1520	-6	.0085	46.5	63

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(ℓ) Run 12; boiler-outlet condition, 70-percent quality; Freon flow rate, 379 pounds per hour (0.048 kg/sec); inlet water temperature, 250° F (394° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\lvert P'_i \rvert$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\lvert P'_i/w'_F \rvert$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.06	43	0.0054	9	0.56	3860	0	0.0130	71.2×10^4	-9
.08	44	.0055	10	.54	3720	-1	.0123	67.4	-11
.10	30	.0038	-4	.30	2070	-42	.0100	54.8	-38
.20	33	.0041	-1	.21	1440	-80	.0064	35.1	-79
.30	33	.0041	-11	.14	960	-161	.0042	23.0	-150
.40	30	.0038	-24	.15	1030	-223	.0050	27.4	-199
.50	29	.0036	-29	.17	1170	-270	.0059	32.4	-241
.60	28	.0035	-31	.18	1240	-302	.0064	35.1	-271
.70	27	.0034	-33	.20	1380	-324	.0074	40.5	-291
.80	26	.0033	-33	.20	1380	-340	.0077	42.2	-307
.90	26	.0033	-33	.20	1380	-355	.0077	42.2	-322
1.0	26	.0033	-33	.18	1240	-368	.0069	37.8	-335
1.12	26	.0033	-32	.15	1030	-382	.0058	31.8	-350
1.25	27	.0034	-35	.11	760	-397	.0041	22.5	-362
1.50	28	.0035	-37	.02	140	-716	.0007	3.8	-679
1.75	28	.0035	-45	.12	830	-666	.0043	23.6	-621
2.00	27	.0034	-50	.21	1440	-686	.0074	40.5	-636
2.12	26	.0033	-51	.23	1580	-692	.0088	48.2	-641
2.25	26	.0033	-54	.25	1720	-706	.0096	52.6	-652
2.37	25	.0031	-55	.26	1790	-717	.0104	57.0	-662
2.50	25	.0031	-54	.25	1720	-725	.0100	54.8	-671
2.75	24	.0030	-56	.22	1510	-736	.0092	50.5	-680
3.00	25	.0031	-58	.22	1510	-739	.0088	48.2	-681
3.25	24	.0030	-61	.21	1440	-745	.0087	47.6	-684
3.50	24	.0030	-62	.20	1380	-757	.0083	45.5	-695
3.63	24	.0030	-63	.17	1170	-768	.0071	38.9	-705
3.75	24	.0030	-65	.14	960	-770	.0058	31.8	-705
4.0	26	.0033	-69	.08	550	-727	.003	16.0	-658

[a]Zero to peak.

TABLE II. - Concluded. BOILER PERTURBATION DATA

(m) Run 13; boiler-outlet condition, 93-percent quality; Freon flow rate, 295 pounds per hour (0.037 kg/sec); inlet water temperature, 250° F (394° K)

Frequency, f, cps (Hz)	Perturbation data for Freon flow at boiler inlet			Perturbation data for pressure at boiler inlet			Boiler-inlet impedance		
	Magnitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, w'_F, deg	Magnitude,[a] $\lvert P'_i \rvert$		Phase relative to oscillator, $\varphi_{p'_i}$, deg	Magnitude, $\lvert P'_i/w'_F \rvert$		Phase, $\varphi_{p'_i} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	17	0.0021	-5	0.92	6340	-25	0.0541	29.6×10^5	-20
.06	20	.0025	5	.94	6460	-27	.0470	25.8	-32
.08	22	.0028	11	1.04	7160	-26	.0473	25.9	-37
.10	21	.0026	12	1.05	7230	-35	.0500	27.4	-47
.20	30	.0038	22	1.12	7720	-60	.0373	20.4	-82
.30	45	.0057	17	1.22	8400	-102	.0272	15.0	-119
.40	56	.0070	-4	1.06	7300	-158	.0189	10.3	-154
.50	52	.0065	-19	.72	4960	-204	.0138	7.6	-185
.60	46	.0058	-28	.51	3510	-241	.0111	6.1	-213
.70	41	.0051	-32	.42	2890	-269	.0103	5.6	-237
.80	38	.0048	-34	.37	2550	-296	.0097	5.3	-262
.90	35	.0044	-34	.34	3340	-317	.0097	5.3	-283
1.0	35	.0044	-33	.31	2140	-335	.0089	4.9	-302
1.25	33	.0041	-34	.28	1930	-372	.0085	4.7	-338
1.5	34	.0043	-33	.21	1450	-400	.0062	3.4	-367
1.75	36	.0045	-37	.12	830	-429	.0033	1.8	-382
2.00	37	.0047	-42	.01	70	-440	.0003	.2	-398
2.25	37	.0047	-49	.07	480	-678	.0019	1.0	-629
2.50	36	.0045	-52	.11	760	-699	.0031	1.7	-647
2.75	35	.0044	-55	.08	550	-712	.0023	1.3	-657
3.00	38	.0048	-61	.12	830	-638	.0032	1.8	-577
3.25	38	.0048	-69	.31	2140	-659	.0082	4.5	-590
3.50	34	.0043	-76	.46	3170	-690	.0135	7.4	-614
3.75	29	.0036	-78	.50	3450	-722	.0173	9.5	-644
4.00	29	.0036	-71	.45	3100	-754	.0155	8.5	-683

[a]Zero to peak.

NASA-Langley, 1967 —— 12 E-3966

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